c.2

RM 51E04

NACA RM 51E04

RESEARCH MEMORANDUM

INVESTIGATION OF TORSION CREEP-TO-RUPTURE

PROPERTIES OF N-155 ALLOY

By C. W. MacGregor and F. J. Walcott, Jr.

Massachusetts Institute of Technology

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
August 21, 1951

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

INVESTIGATION OF TORSION CREEP-TO-RUPTURE PROPERTIES OF N-155 ALLOY

By C. W. MacGregor and F. J. Walcott, Jr.

SUMMARY

This report describes an investigation of the torsion creep-to-rupture properties on the alloy steel N-155. Rupture times in the 10-to-1000-hour range were considered and tests were made at the temperatures 1200°, 1350°, and 1500° F. The effect of stress concentration in the form of transverse circular holes was investigated under the same conditions. Comparisons of the effects of simple combined stresses (as in torsion) were made with tension creep-to-rupture properties.

It was found that the ratio of the shear stress to tensile stress for a given time to rupture was about 0.74 for both long- and short-time tests at 1200° and 1350° F, but varied from this figure to about 0.65 for the short-time tests at 1500° F. The effect of the stress concentration produced by circular holes was to reduce the time to rupture at 1200° F by a factor of 25. At 1500° F this factor was approximately 3.

INTRODUCTION

Although the effect of combined stresses on creep has received some attention (references 1 to 3), there is practically no information available on their influence on creep-to-rupture properties (reference 4). This is in spite of the fact that states of combined stresses are present in most machine parts where creep-to-rupture properties are important.

In addition, the influence of stress concentration, which again is usually present to varying degrees in most designs, on the creep-to-rupture properties is practically unknown.

The present investigation, while largely limited to torsion, is an attempt to supply some useful data on these hitherto unsolved problems as it refers to the alloy steel N-155 of importance in gas-turbine applications. A description of the apparatus is given together with the testing method adopted. Following this a discussion is presented of the results including the effects of combined stresses and stress concentration on the creep-to-rupture properties of this alloy.

This investigation was conducted at the Massachusetts Institute of Technology under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics. The authors wish to acknowledge the interest and support received during this work from the various members of the Subcommittee on Heat-Resisting Materials of the NACA and from Professor C. R. Soderberg of the Massachusetts Institute of Technology. Professor N. J. Grant was particularly helpful in connection with the study of the crack formation and with general advice on various phases of the program.

DESCRIPTION OF APPARATUS

The general arrangement of the testing frame is shown in the accompanying photographs. Figure 1 shows the entire frame with the furnace in position. The specimen is positioned by a shaft from above and a rugged bearing b below. The latter consists of a 4-inch-square inner piece, a hollow square block, and rollers in between, so that the specimen although constrained from rotation is free from any axial load. Because of the weight of the inner piece of the bearing, two counterweights c must be provided to eliminate any axial stress in the specimen.

The general features of the loading arrangement are seen in figures 1 to 3. The torque is applied as a couple by two wires going on to a 24-inch pulley j which is clearly seen in figure 2. These wires are in turn loaded by two levers d, one on each side of the machine. From the outer ends of these levers are suspended weights on a scale pan, while on the ends of the levers nearer to their fulcrums there are counterweights s (fig. 3) which obviate any tare correction in calculating torque.

The loading system has been designed to apply either a clockwise or counterclockwise torque; to this end there are actually four wire connections to the main pulley j, one pair corresponding to the clockwise torque and the other to the opposite torque.

Restricting discussion to one of the levers, the operation of the system will be described. A wire comes off the main pulley j over the appropriate one of the sheaves K (fig. 2) and goes down and around one of the two sheaves r at the lever d. These sheaves are seen in figure 3 and are attached to small weights. Depending on the direction of the torque, either one or the other of these sheaves bears against the lever. From this sheave the wire goes up to a take-up drum h (fig. 2) driven through a gear reducer e by a motorized reducer f.

As the specimen deforms, the pulley j rotates and the lever d drops. When this proceeds far enough, a microswitch at t (fig. 3) actuates the motorized gear reducer f and as the take-up drum h revolves, the lever is restored to its initial position. The wire leaving the take-up drum goes down to that one of the small sheaves r which is not bearing against the lever d and back up to feed on the main pulley j. This comparatively slack wire, having gone through one of the small sheaves r, has a definite tension due to the attached weight of the sheave which prevents slipping on the take-up drum h and assures its correct feeding on to the pulley j. It incidentally exerts a back torque on the specimen, but this effect is exactly cancelled by the contribution of the weight attached to the other sheave which is bearing against the lever.

This system has distinct advantages. It allows as much as three full turns of the specimen without having large weights which might drop through a considerable distance upon fracture of the specimen. This is a worth-while feature since there are nine other creep frames in the same laboratory. In addition, the torque may be easily reversed without disturbing the specimen although this is of no significance in the present investigation.

Figure 3, in which the furnace has been removed, shows the connections of the test specimen. Between the shaft v, the inner piece of the bearing b, and the specimen q there are adaptors c. The torque is applied through tang and groove connections between the various members. (These are concealed by the sleeves p and nuts n.) The adaptors have been included because the parts close to the specimen get extremely hot and it was feared they might suffer some distortion.

In the course of normal operation no such distortion has occurred, although in one run a specimen was not properly seated and severe deformation of the grip resulted, necessitating repair of the part. A further advantage of the adaptors lies in the fact that a modification of the specimen from 12- to 4-inch over-all length with no change in test section could be made without requiring great changes in the testing machine itself. This modified specimen shown in figure 4 has resulted in an appreciable reduction of machining costs because of a decrease in drilling time.

The angular strain is measured and recorded by fixing grips within the hollow specimen. One of these is attached to a tube which in turn is attached to a brass commutator m (fig. 2), while the other is attached to a rod which goes through the tube and is attached to an arm l carrying a stylus. The surface of the commutator is formed of alternate strips of conducting and nonconducting material.

This relative motion causes the stylus to cross from conducting to nonconducting regions, fixed increments of strain causing either the make or break of an electric circuit which is recorded by a multistation time clock. This time clock handles information from six creep units and stamps both time and an appropriate identifying symbol on a paper tape similar to those used in adding machines. Thus the times at which fixed increments of strain occur are taken from the time-clock tape by copying all time stamps accompanied by the symbol designating the particular creep machine.

It was found that the commutator gave many extraneous indications since vibrations could cause the stylus to jump from conducting to nonconducting regions. Although these were, in general, close enough in time to the correct indication to be interpreted correctly as extraneous, they did lead to some confusion. Since the magnitude of rotation of the torsion creep specimens was so large, there was no need for as many indications as were possible with the commutator. Accordingly, a 180-tooth gear was substituted with a microswitch arm replacing the stylus. In the course of the test, relative motion between these two caused the end of the microswitch arm to follow the gear-tooth profile so that for every tooth, of 2°, the microswitch would make and break the time-clock circuit. Although the "make to break" and "break to make" intervals were not the same without very careful adjustment of the position of the microswitch, every alternate reading, that is, only "makes" or "breaks," provided more than enough points to define the creep curves.

In spite of the fact that several tests were run using the gear-microswitch arrangement without noticing any irregularity in readings it was feared that the gear-tooth profile, which had definite corners, might at some time cause the microswitch arm to become caught to such an extent that elastic deflections or even creep in the strain-measurement system might become appreciable. Instead of trying to smooth the gear-tooth profile by machining, an easy substitute was reached by substituting a 112-tooth chain sprocket that had a very smooth tooth profile which is followed very readily by the roller end of the microswitch arm.

This time-clock system of strain measurement has been applied successfully to two other types of testing machines in the Creep and Plastic Flow Laboratory. Its operation is independent of working hours and hence a test in the difficult 1- to 4-day range may be recorded in its entirety without large gaps in the data. Unfortunately, the weak spot in the system is the commercial time clock - the two clocks in this laboratory having had a very poor performance record. At least six servicings and one factory rebuilding apiece have failed to eliminate this trouble. The manufacturer is at this time building modified replacement units of new design to remedy the difficulty which consists of sudden departures from the correct time. Such errors can often be detected by close checking of the time recorders to avoid inclusion of erroneous data, but much time was lost by the erratic behavior of the clocks.

The temperature-control system in this laboratory employs Brown Electronik controllers which may be seen together with the rest of the control system in figure 5. These instruments, which are of the on-off type, have a control-point sensitivity of about $\pm 1^{\circ}$ F. They actuate relays which throw a resistance in or out of series with the furnace windings so that the whole system may be described as "on - partially off." The two steady-state temperatures corresponding to the series resistance "in" and "out" straddle the control temperature sufficiently so that the demands caused by the greatest possible changes in ambient temperature may be met.

The specimen is fitted with five thermocouples, one going to the controller, one to a multistation recorder, and three to a switch panel for reading by a type K potentiometer. These three are used for the setting of temperatures at the beginning of the test and act as a check on the accuracy of the set-point of the controller.

TEST PROCEDURE

The operation of the equipment in connection with the creep-to-rupture testing procedure for plain specimens has been covered in the section "Description of Apparatus." The strain-measuring and recording devices are automatic, although, as noted earlier, poor time-clock performance necessitated frequent checks and the eventual installation of an independently actuated periodic signal to give an automatic running check.

For tests using stress-concentration specimens in which the deformation is a combination of that localized around the hole and that in the rest of the specimen, the more elaborate recording of the relative motion of two planes at the extremities of the gage length was not considered worth while. Instead, the head motion of the machine was recorded which included the elastic deflection of the shaft and the grips. The greatest possible error thus introduced is about 0.01 in the fracture strain values reported in table I, the errors always being such that the tabulated values are too high.

TEST RESULTS

Figure 6 and table II give a summary of the torsion stress-rupture data. It is seen that these data may be represented by a logarithmic stress-rupture-time curve in much the same way as for tension stress-rupture data. Some of the fractured specimens for these tests are shown in figure 7.

An 0.080-inch wall thickness was used for all of the tests at 1200° F and all but three of the tests at 1350° and 1500° F used specimens with a wall thickness of 0.100 inch. As may be seen from the photographs the specimens exhibit varying degrees of unsymmetrical distortion after fracture. This is to be expected since once the fracture has begun the symmetry originally existing has been destroyed. In addition, the fractures are not complete in the sense that the specimens are separated into two distinct pieces and the design of the machine is such that the load is not removed after the sudden deflection indicating failure, but decreases during a relaxation process as the upper section of the specimen rotates relative to the fixed lower part. Depending on the position of the loading lever arms this distortion after fracture may add an additional rotation of the order of 5° to the final twist of the specimen.

A comparison of tension and torsion stress-rupture data as shown in figure 6 shows that the tension and torsion curves are very nearly parallel. Stated another way, τ/σ, the ratio of shear stress to tension stress to produce rupture in a given length of time, is very nearly constant at 1200° and 1350° F. This stress ratio for both the short- and long-time portions of the curves is given in table III.

The tension stress-rupture data are for stock from the same heat of low-carbon N-155 (heat A-1726) having the same heat treatment, that is, 1 hour at 2200° F followed by a water quench and aging for 16 hours at 1400° F.

This information is from two sources: Unpublished data, subject to revision, furnished by Dr. James Freeman of the University of Michigan and the results of tests performed in the Metallurgy Department of M.I.T, using specimens cut from the same bar stock as was used for machining the torsion specimens and from such a position that both the axis of the tensile specimens and the mean radius of the wall of the torsion specimens lay at the same radial position in the unmachined stock.

The type of fracture varies considerably as seen from figure 7. At 1200° F the over-all appearance of the fracture for short-time tests is suggestive of a tension crack of a helical nature. Closer examination shows, however, that the cracks having this appearance are really composed of stepwise alternate axial and tangential portions. At the higher temperatures, in general, cracks ran circumferentially indicating a true shear failure.

Metallurgical examination of some specimens at first showed no regularity as to whether failures were transcrystalline or intercrystalline. It was realized that much depended upon the selection of the correct area for examination, that is, the area where the crack was initiated. Once the crack was formed, the original state of stress was considerably altered. Accordingly, more specimens were examined with particular care being paid to the determination of the actual origin of the fracture. Two specimens for each of the three test temperatures were studied, one for a test of short duration and one for a longer period. As may be seen in table II, all of these cracks (except for the long-time test at 1500° F) are predominantly transcrystalline. A typical photomicrograph is shown in figure 8.

Figures 9 to 11 show strain-time curves for three different temperatures. The test results for specimens through which a 1/8-inch transverse hole had been drilled are presented in figure 12 and table I. Figure 13 shows a typical fractured specimen for each of the three temperatures. The failures are of the tension type with a smooth crack emanating from each side of the hole.

The effects of this stress concentration are very marked indeed, and are presented in two forms in table IV.

The stress-concentration factor in table IV is defined as the ratio of the nominal shear stress for a plain specimen to the nominal shear stress for a stress-concentration specimen needed to produce rupture in a given time. The time-to-rupture factor is the ratio of rupture life for plain specimens to the rupture life for stress-concentration specimens at the same nominal stress level.

DISCUSSION

Perhaps the most striking difference between tension and torsion creep-to-rupture curves is the superficial difference in shape of the two types of curves. A glance at figure 9 shows, especially for the longer tests, that the linear portions of the torsion creep curves are relatively small as compared with those received in tension creep tests; that is, secondary creep comprises a much smaller portion of the time to rupture for this material.

Figure 14 shows a more valid comparison than that mentioned above. Here, both tension and torsion creep curves are plotted together with shear strains from the torsion tests appropriately reduced by the factor $\sqrt{3}$. The two torsion creep curves are seen to fit into the family of tension creep curves for the moderate values of strain included in the figure. However, the three tension creep curves adjacent to the two torsion curves are represented in their entirety, excluding the short period of rapid strain immediately before fracture, whereas only one-fourth of the total strain and one-third of the total time is included for the torsion creep curves.

Hence the relationship between tension and torsion creep curves might be summarized as follows:

Up to equivalent strains nearly corresponding to the final secondary creep strains in the tension test, tension and torsion creep curves are somewhat similar. However, beyond these values of strain, the tension specimen experiences a rapid straining leading to early fracture while the torsion specimen continues at nearly constant strain rate for a time and then with ever-increasing strain rate to fracture. The period of similarity between the two types of tests represents almost the total time to rupture for the tension test but only about a third of the period of the torsion test with this alloy.

The fracture surfaces studied near the origin of fracture showed predominantly transcrystalline failures as seen in table II, the one exception being the long-time test at 1500° F. Figure 8 shows a transcrystalline failure typical of those at the lower temperatures.

Examination of these specimens showed widely varying grain sizes and the failures were in general mixed, but could be labeled predominantly transcrystalline. It is possible that the one exception noted above was due to the uncertainties involved in locating the origin of fracture.

Assuming the majority of the fracture evidence to be correct, it agrees well with a creep-failure theory proposed by Siegfried (reference 5). This argument explains a break in the logarithmic stress-time-to-rupture curve and its accompanying change from transcrystalline to intercrystalline failure by reasoning that the former, associated with shear, is due to the deviator component of a state of stress while the latter is due to the hydrostatic stress component. As a result, in the general state of stress in which both components are present failures may be mixed, even at a single temperature depending on which component is controlling at any particular rupture life. The interesting consequence of this is that for hydrostatic tension having no deviator component failure could be only intercrystalline, while for pure shear with no hydrostatic component failure could be only transcrystalline. This latter seems to be in good agreement with the findings of the present investigation. However, torsion tests should be conducted on alloys showing greater embrittling tendencies in tension than the present material to determine if Siegfried's concept is generally valid.

Shear strains at fracture for this alloy vary both with the time of testing and the temperature as seen in table II. At both 1200° and 1350° F there is in general a decrease of fracture strain with decreasing time to rupture while at 1500° F there is an increase of fracture strain for decreasing time to rupture, although the one rapid test shows greatly decreased ductility. It must be noted, however, that there is too much spread in the data to attempt to draw any quantitative conclusions. It may be stated, however, that in general fracture strains increased with increasing temperature.

The effects of stress concentration are seen to be most pronounced at 1200° F and although comparatively small at 1500° F, these effects are still present to a noteworthy degree. There is great scatter in the average fracture strains although, again, a trend toward higher values at higher temperatures. The "nominal fracture strain" reported is closer to an average strain over the entire specimen at fracture than to a localized strain at the source of stress concentration.

The effect of stress concentration even for this relatively mild source, namely the circular hole, is a matter of practical importance because of the tremendous effect on time to rupture at a given value of nominal stress. The rupture-life factor of 3.33 at 1500° F may be small compared with a factor of 25 at 1200° F but it is still a matter of vital concern in design work.

Massachusetts Institute of Technology
Cambridge, Mass., November 22, 1950

REFERENCES

1. Everett, F. L., and Clark, C. L.: Report on Torsion Creep Tests for Comparison with Tension Creep Tests on a Carbon Moly-Steel. Proc. A.S.T.M., vol. 39, 1939, pp. 215-225.

2. Tapsell, H. J., and Johnson, A. E.: Creep under Combined Tension and Torsion. Engineering, vol. 150, no. 3887, July 12, 1940, pp. 24-25; no. 3889, July 26, 1940, pp. 61-63; no. 3891, Aug. 9, 1940, pp. 104-105; no. 3892, Aug. 16, 1940, p. 134; no. 3894, Aug. 30, 1940, pp. 164-166.

3. Johnson, A. E.: The Plastic Creep and Relaxation Properties of Metals. Aircraft Eng., vol. XXI, no. 239, Jan. 1949, pp. 2-8.

4. Siegfried, W.: Creep Tests and Their Application to Gas-Turbine Design. Sulzer Tech. Rev. No. 4, 1948, pp. 21-33.

5. Siegfried, W.: Failure from Creep as Influenced by the State of Stress. Jour. Appl. Mech., vol. 10, no. 4, Dec. 1943, pp. A-202 - A-212.

TABLE I

FRACTURE DATA OF TESTS WITH STRESS CONCENTRATION

Temperature ($^{\circ}F$)	Nominal shear stress (psi)	Time to rupture (hr)	Average fracture strain [1]
1200	24,130	322	0.073
	29,000	32.8	.105
	31,900	12.5	.147
	34,500	7.5	.178
	38,200	1.4	.220
1350	13,970	606	0.294
	17,460	53.8	.283
	19,970	25.8	.314
	24,150	6.6	.094
	26,500	5.3	.115
	26,500	4.3	.063
1500	8,900	534	0.272
	10,320	174	.388
	11,720	56.9	.430
	14,080	14.8	.358
	17,820	2.2	.210

[1]Taken from head motion of testing machine. Includes elastic deflections.

NACA

TABLE II

SUMMARY OF DATA

Temperature (°F)	Wall thickness (in.)	Shear stress (psi)	Time to rupture (hr)	Shear fracture strain, γ_F	Type of failure
1200	0.080	29,200	666	0.583	Transcrystalline
	.080	31,700	323	.522	
	.080	37,900	52.5	.362	
	.080	37,900	44.4	.312	
	.080	40,000	29.4	.279	
	.080	40,000	22.0	.368	Transcrystalline
1350	0.100	18,050	[a]482	0.841	
	.100	20,100	161	1.06	
	.100	21,300	108	.875	
	.080	22,750	75	.724	
	.080	22,750	75	.789	
	.100	25,200	36.3	.774	
	.100	25,200	34.6	.909	Transcrystalline
	.100	25,000	39.5	.841	
	.100	24,850	28.1	.378	
	.100	31,900	4.1	.659	
1500	0.100	10,320	[b]568	1.005	Intercrystalline
	.100	11,300	225	.774	
	.100	12,660	103	1.04	
	.100	14,070	50	1.18	
	.100	14,870	38.9	1.12	Transcrystalline
	.100	15,660	18.8	1.26	
	.100	22,100	[c]1.12	.335	

[a]±10 hr - failure of time clock.

[b]Some strain recordings missed because of time-clock failure.

[c]Time to apply full load is appreciable, approx. 15 min.

TABLE III

COMBINED-STRESS EFFECTS

Temperature (°F)	Ratio of shear to tensile stress for given rupture life, τ/σ	
	Short-time tests	Long-time tests
1200	0.74	0.74
1350	.73	.74
1500	.65	.73

TABLE IV

SUMMARY OF STRESS-CONCENTRATION EFFECTS

Temperature (°F)	Average stress-concentration factor	Average time-to-rupture factor
1200	1.33	25.0
1350	1.27	7.5
1500	1.16	3.33

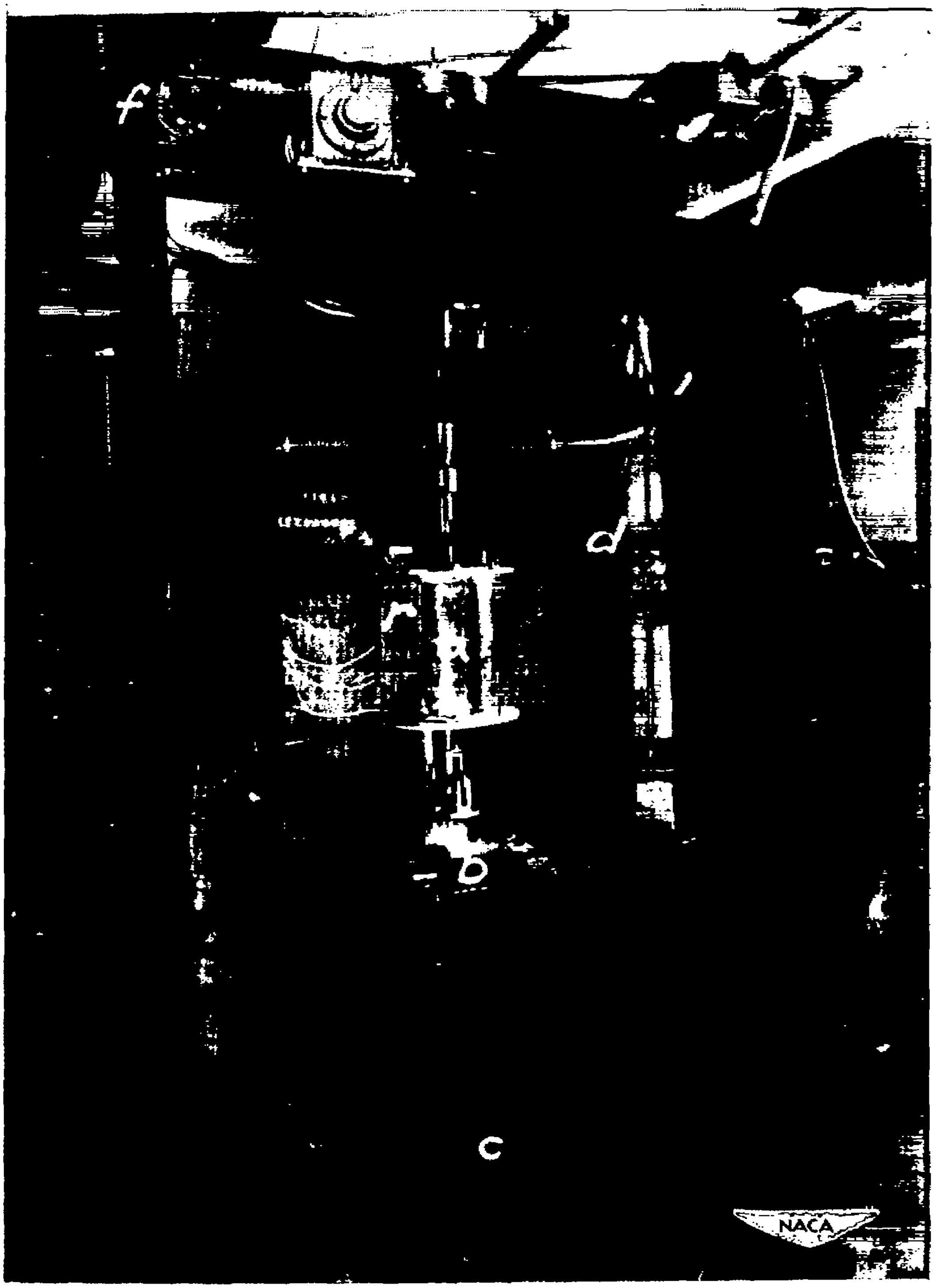


Figure 1.- Entire testing frame with furnace in position.

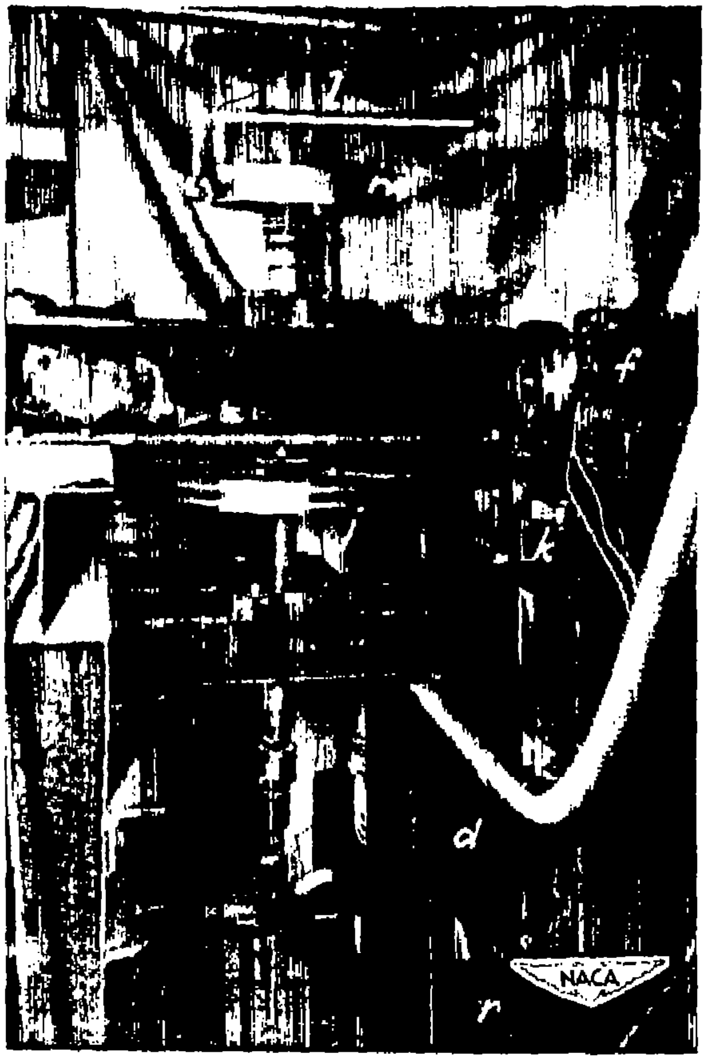


Figure 2.- Close-up view of test frame.

Figure 3.- Connections of test specimen.

NOTE A: BORE & O.D. MAY BE ± .005 IF WALL THICKNESS IS .1000 ± .0005.

NOTE B: IN FORMING FILLETS AT ENDS OF TEST SECTION PARTICULAR CARE IS TO BE EMPLOYED TO AVOID UNDER CUTTING.

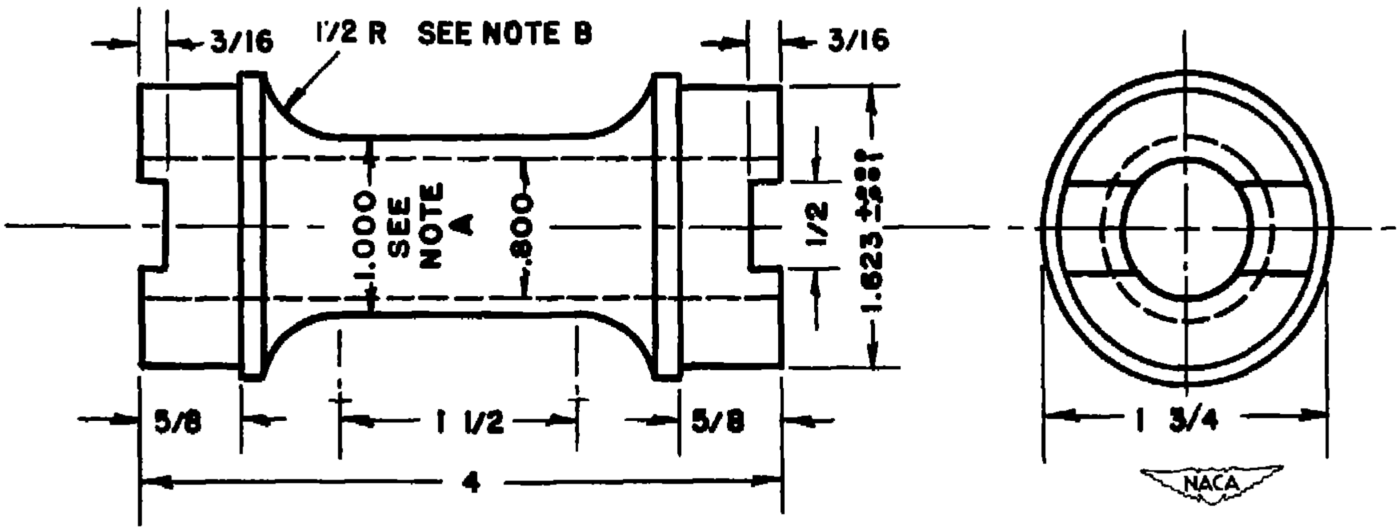


Figure 4.- Modified torsion creep specimen.

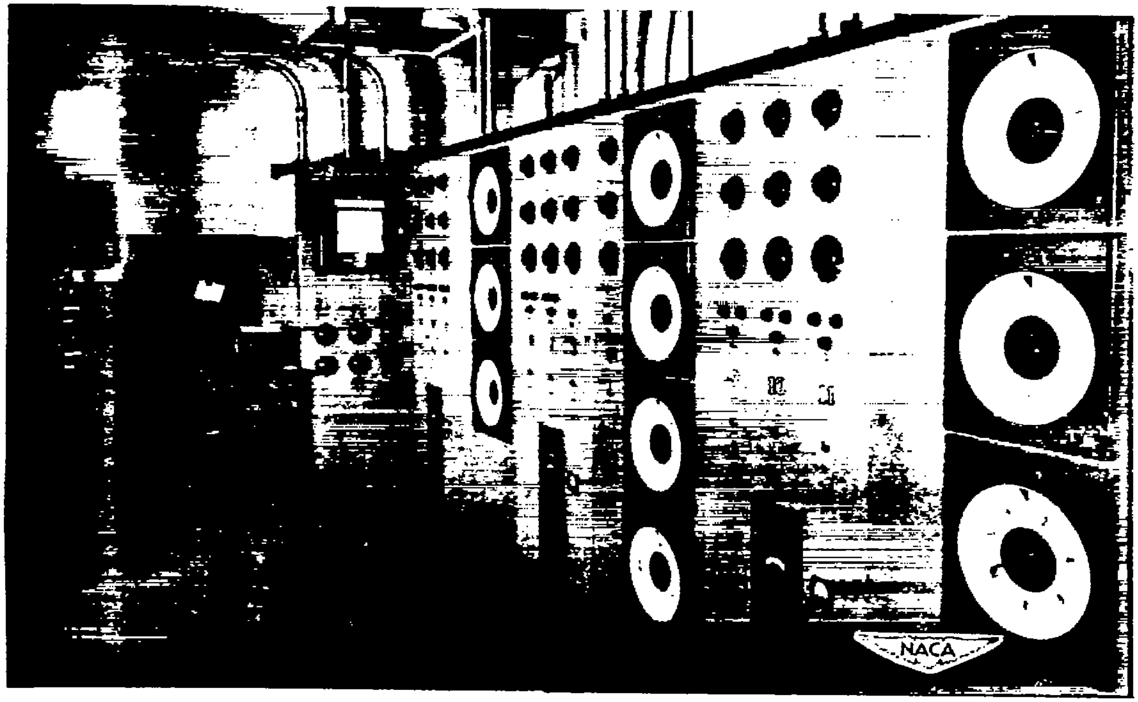


Figure 5.- Control system.

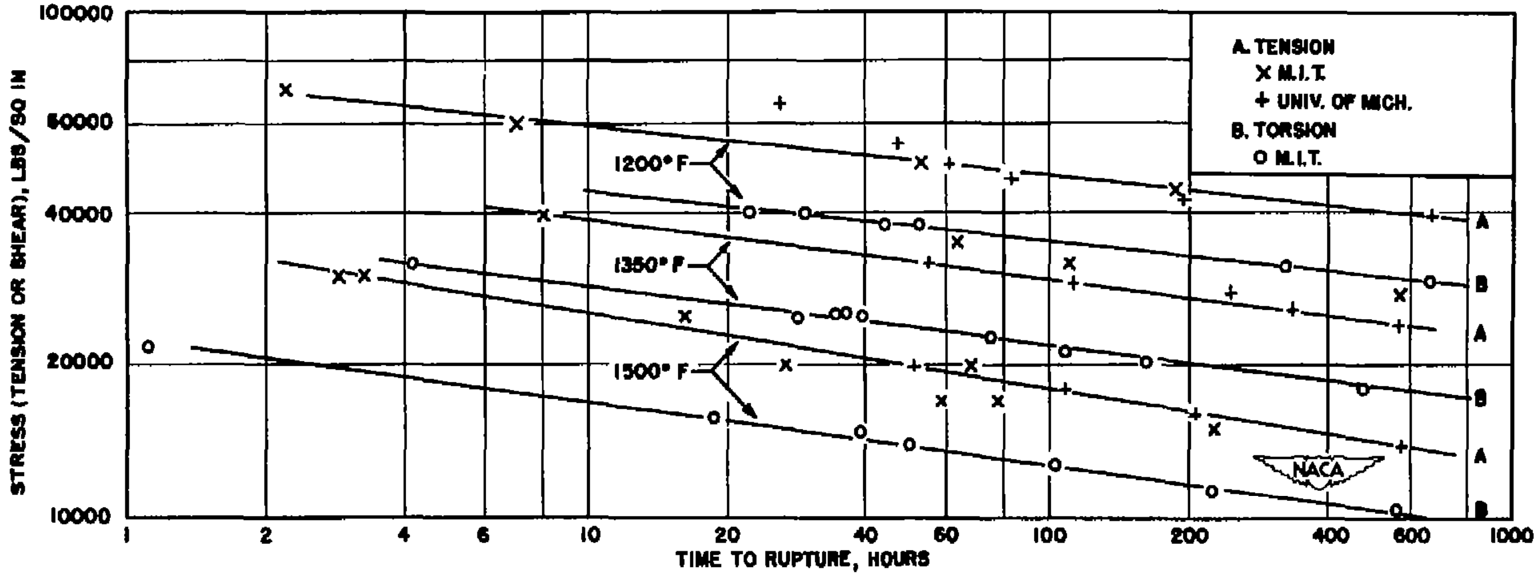


Figure 6.- Comparison of tension and torsion stress-rupture data.

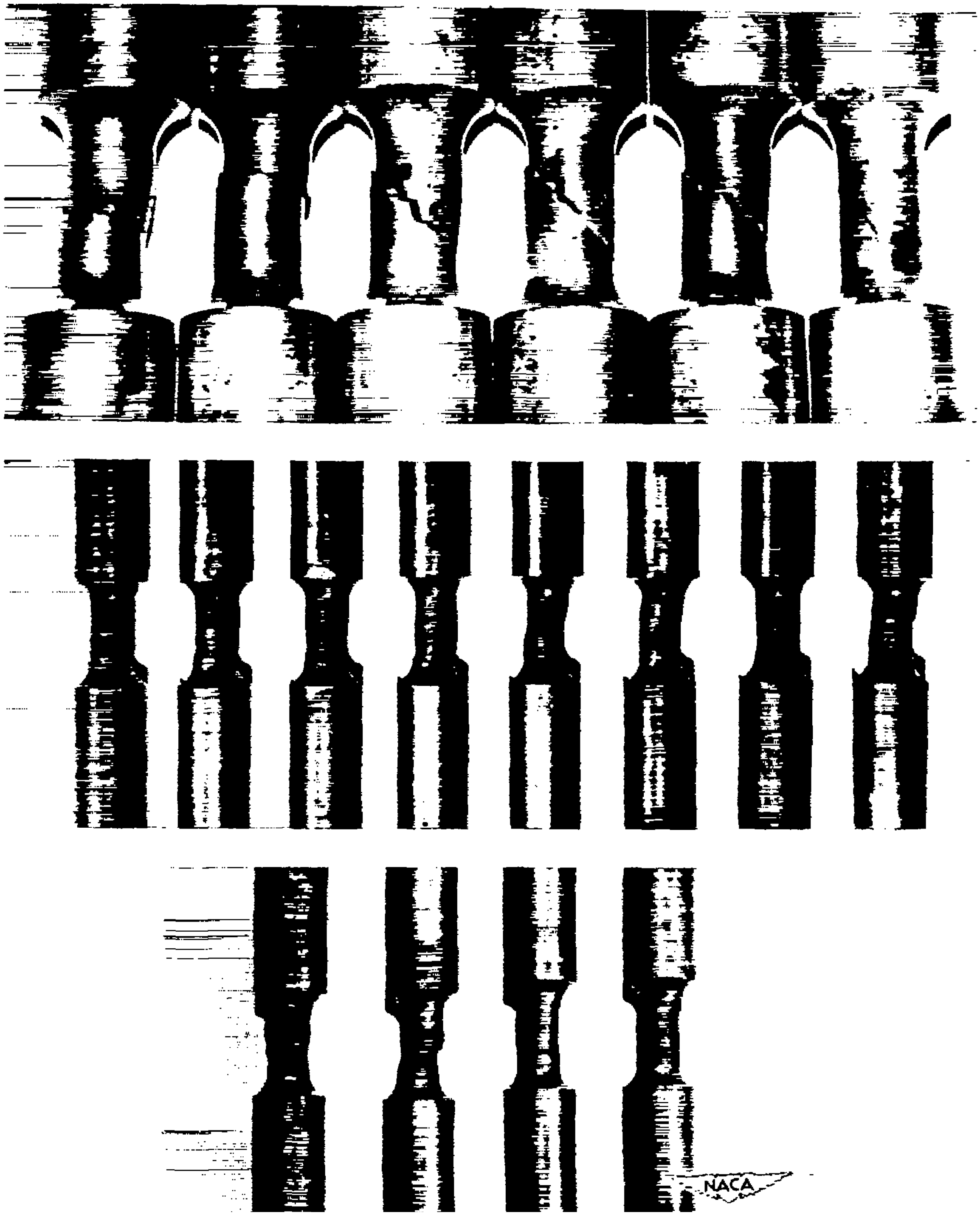

NACA

Figure 8.- Photomicrograph of fracture.

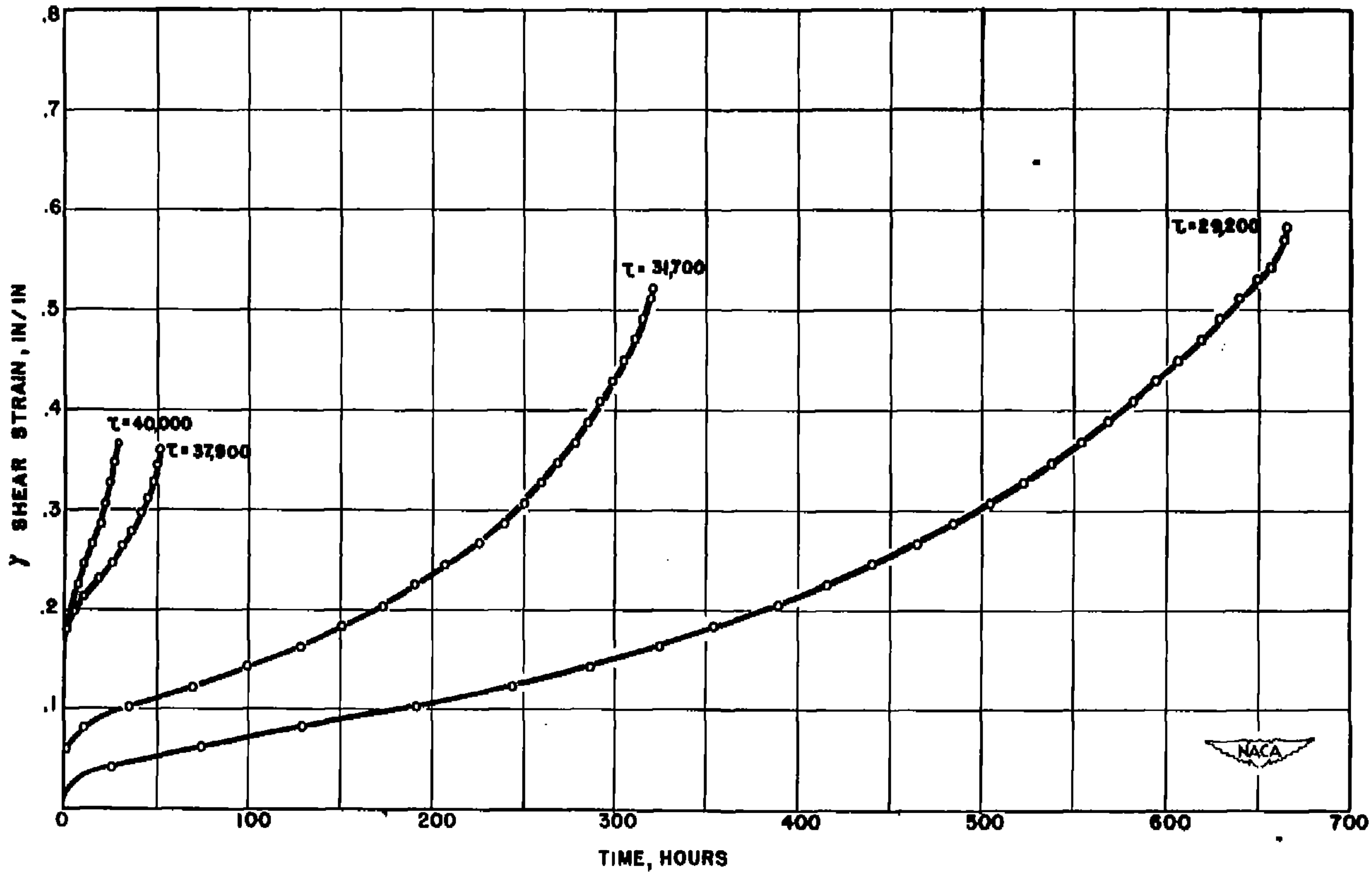


Figure 9.- Torsion creep curves at 1200° F.

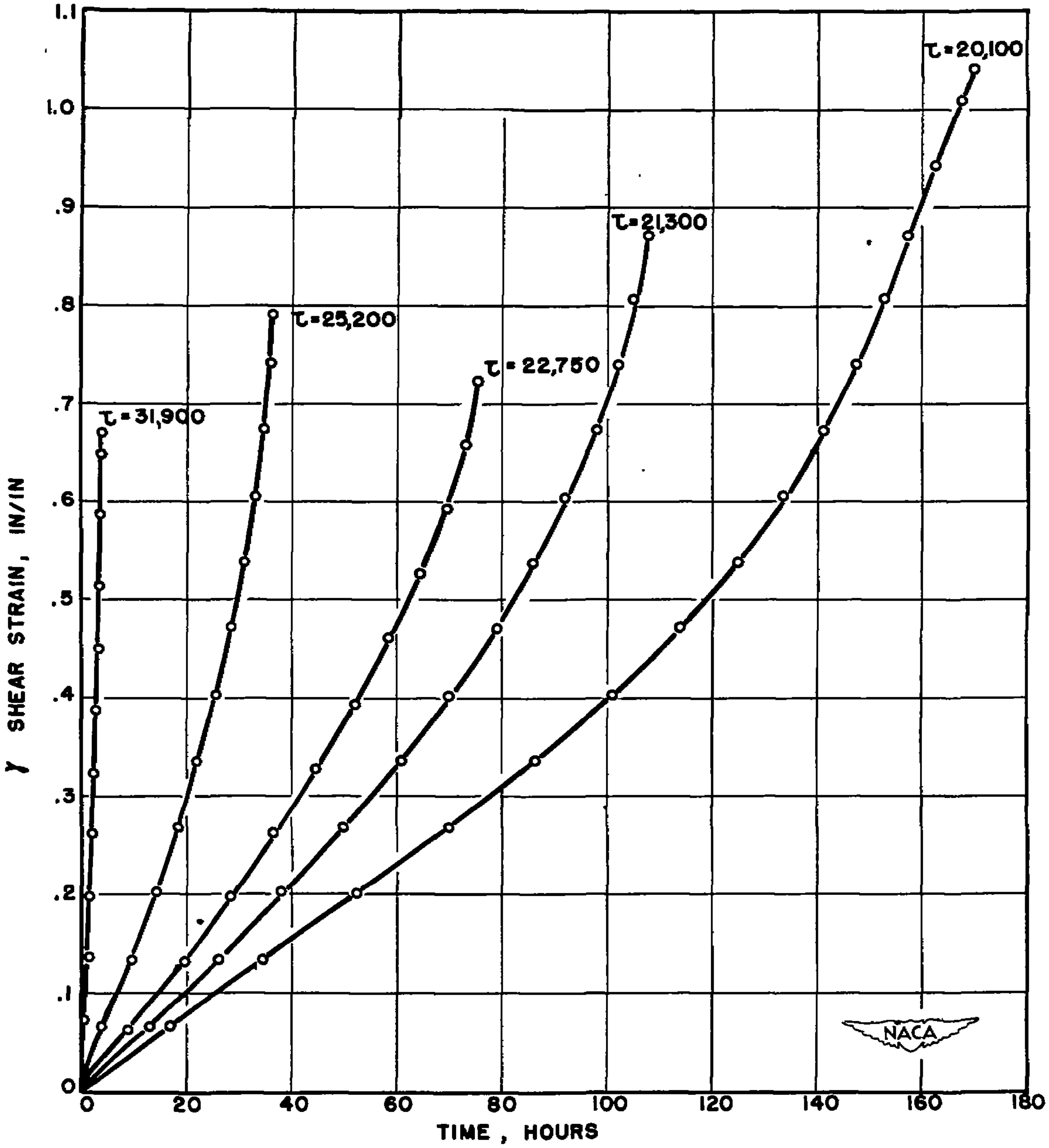


Figure 10. Torsion creep curves at 1350° F.

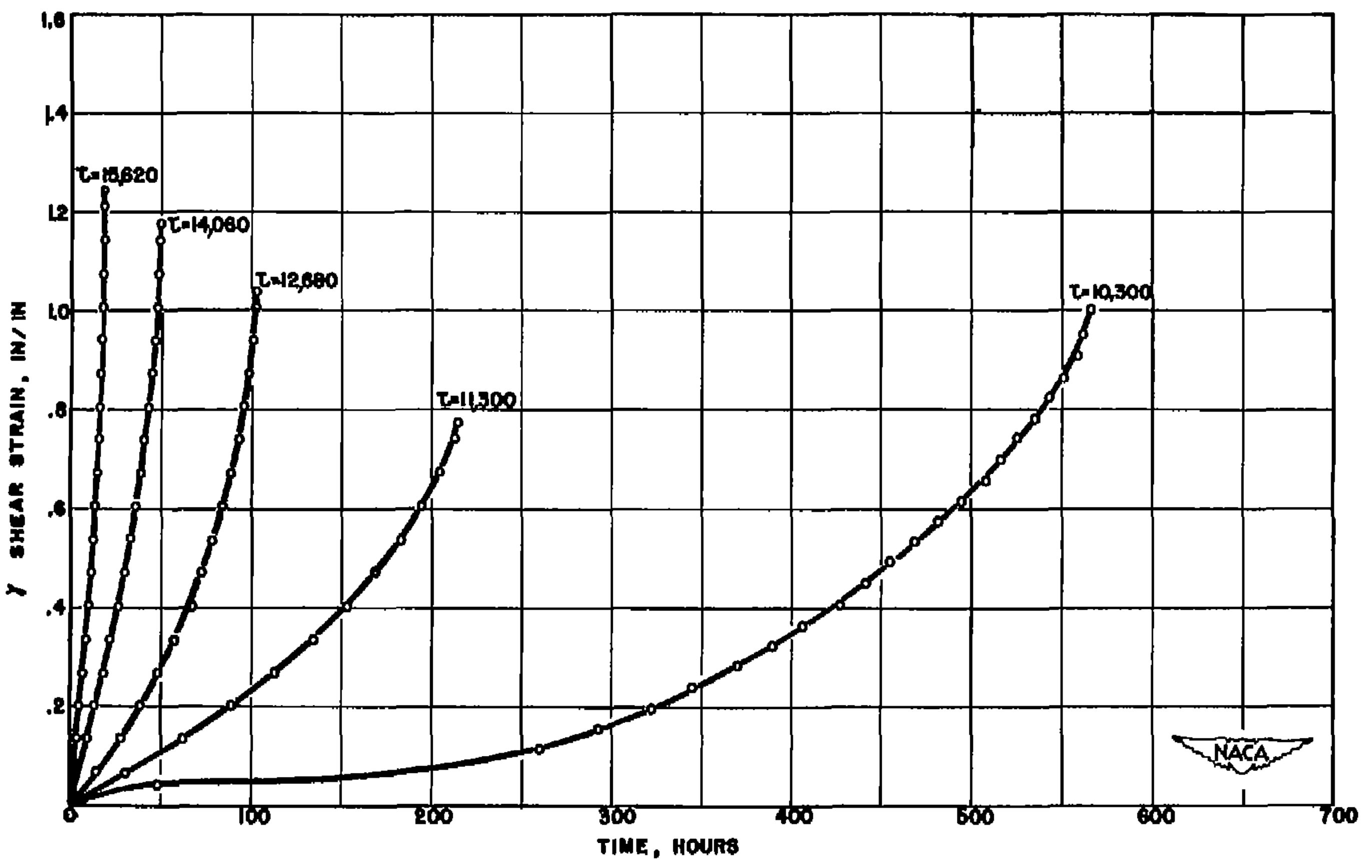
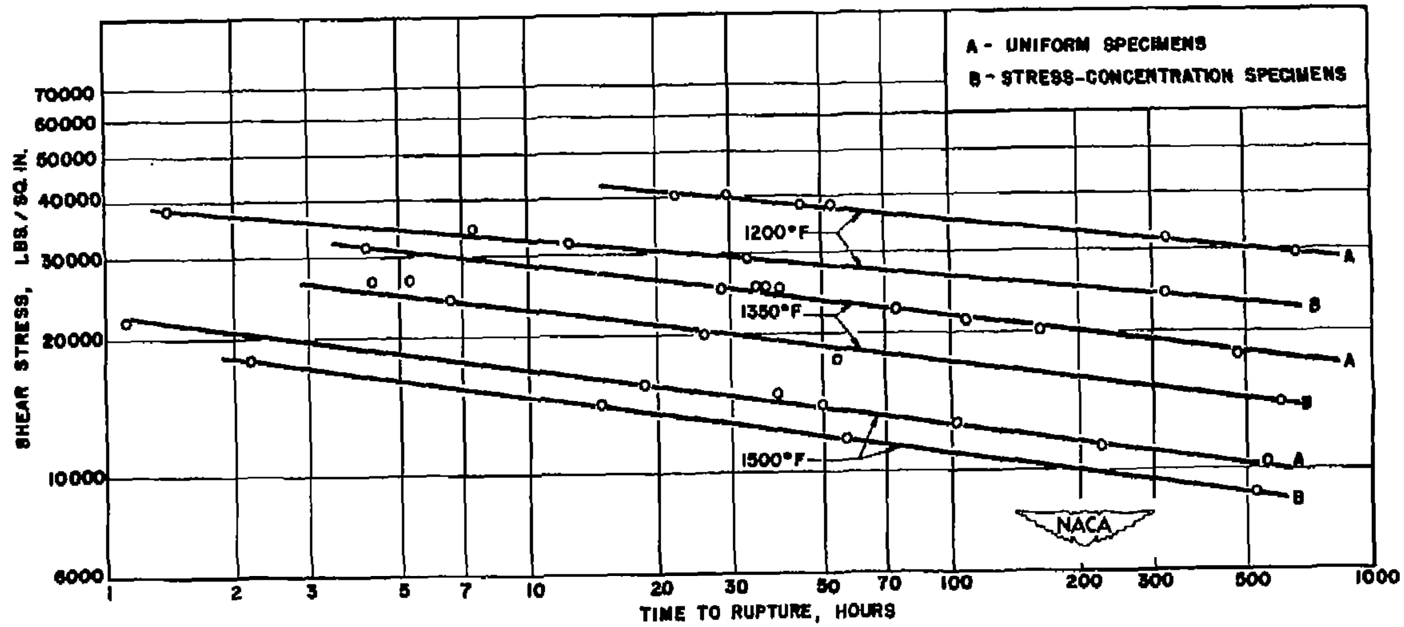


Figure 11.- Torsion creep curves at 1500° F.



EFFECT OF STRESS CONCENTRATION ON TIME TO RUPTURE

Figure 12.- Effect of stress concentration on time to rupture.

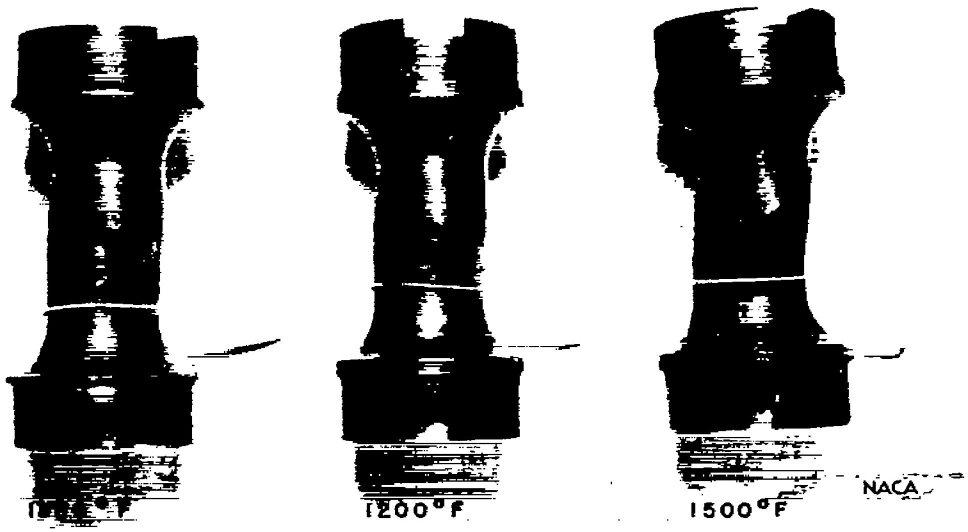


Figure 13.- Typical fractured specimen for each of three temperatures.

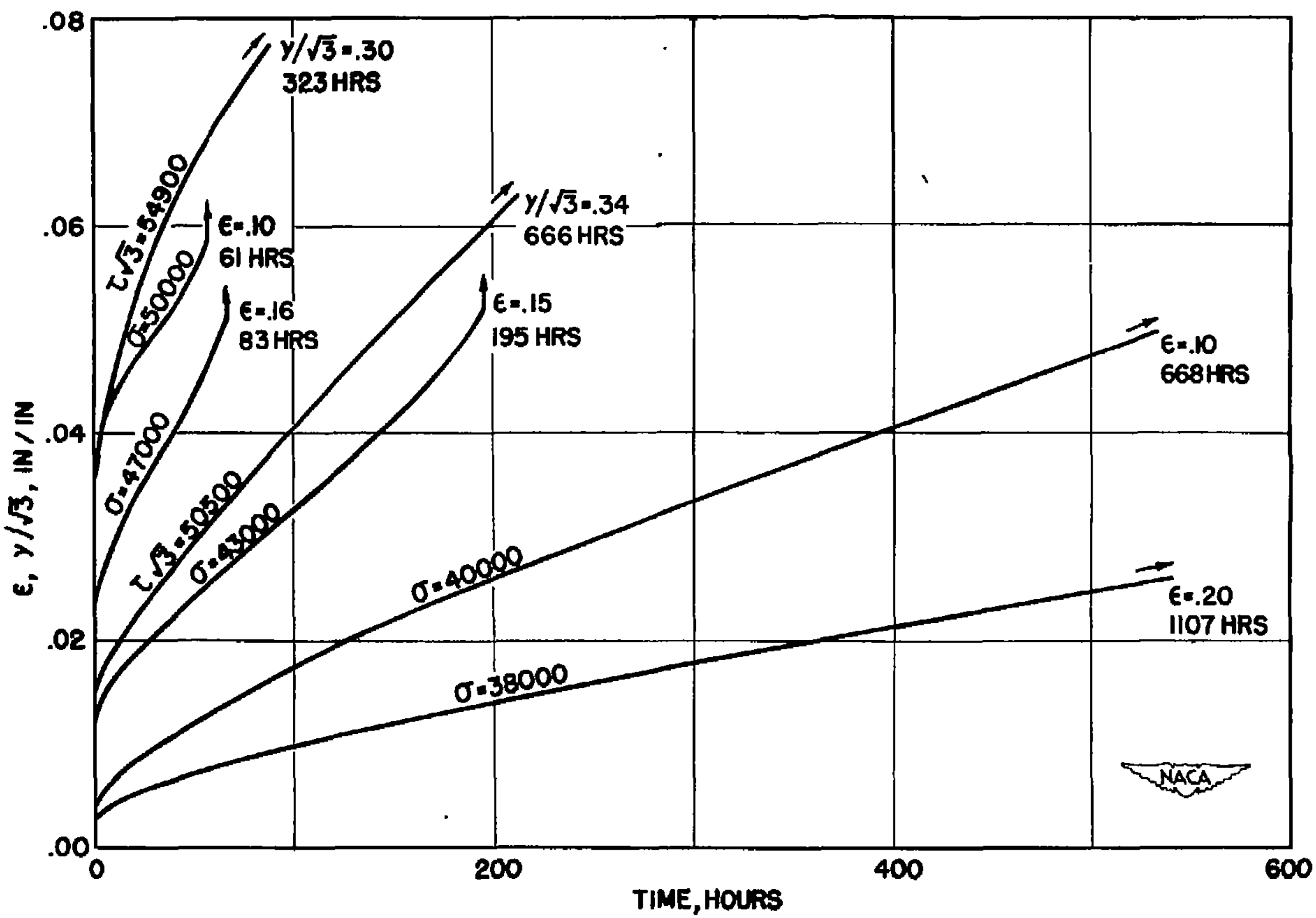


Figure 14.- Comparison of tension and torsion creep curves at 1200° F. Tension data were furnished by University of Michigan; torsion data were furnished by M.I.T.

NACA-Langley - 8-21-51 - 325